HEALTH MONITORING OF COMPOSITE STRUCTURES USING ULTRASONIC GUIDED WAVES

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Abstract:

Health monitoring of composite structures is of prime importance especially for vehicles that may be confronted to high mechanical loads, thermal fatigue or moisture ageing along their service. Structural Health Monitoring may concern not only reusable vehicles undergoing short but high solicitations but also the structures (missiles for instance) that are subjected to long-term storage in harsh environmental conditions.

Therefore some ASTRIUM SPACE Transportation researches currently concern the development of reliable non-destructive inspection methods able to check the long-term integrity of composite materials. This subject is extended to adhesive bonding also used at ASTRIUM-ST to join composite components. Non-destructive methods are also actively studied to monitor these adhesive bonding performances (assessment of adhesion and cohesive properties of bonding).

In this frame, ultrasonic guided waves (or Lamb waves) have been identified as a very promising technique for health monitoring of composite materials and assessment of adhesive bonding quality and integrity. Thus some academic studies have been initiated by ASTRIUM-ST in order to evaluate the sensitivity of these waves to several kinds of solicitations that may operate on our composite structures.

This paper presents the results obtained with academic tests performed on composite plates that have undergone hydrothermal ageing/drying cycles inducing increase in moisture content and low temperature exposure inducing microcracking. The sensitivity of ultrasonic guided waves to these two kinds of solicitations is illustrated.

Finally, the application of ultrasonic guided waves to the characterization of adhesion and the health monitoring of bonding is discussed and preliminary results are presented.

Keywords: health monitoring, composite materials, adhesive bonding, ultrasonic guided (Lamb) waves.

1 INTRODUCTION

Since several years, ASTRIUM SPACE Transportation investigates the needs for introduction of Health Monitoring functions into the composite structures developed for military or civilian launchers. Most of these applications requires to assess the integrity and durability of the structures that may undergo high mechanical loads, thermal solicitation (low and high temperatures), and moisture ageing (during lifetime of several dozens of years).

In this frame, ultrasonic guided waves have been identified as a very promising technique for health monitoring of composite structures [1] and some academic studies have been launched by ASTRIUM-ST in order to evaluate the sensitivity of these waves to several kinds of solicitations that may operate on our composite structures. Moreover, the study of ultrasonic guided waves sensitivity has been extended to the assessment of adhesive bonding quality and integrity during manufacturing in a first step, and throughout the service life of the products in a second step (health monitoring approach).

First of all, a PhD has been initiated in 2001 within the framework of the ADTMRA (Association pour le Développement des Technologies pour la Maîtrise de la Rentrée Atmosphérique) [2]. The goal of this study was to evaluate the ultrasonic guided waves technique to assess the durability of a composite structure undergoing moisture ageing (applications of missile composite vessels) or thermal fatigue (cryogenic tanks application).

Dealing with the adhesive bonding quality assessment, ASTRIUM-ST has focused his approach towards a fundamental study based on the sensitivity demonstration of ultrasonic guided waves to adhesive bonding characteristics (such as surface roughness, glue stiffness…) on academic material (aluminium).

For these two studies, in parallel to experimental investigations, a modelling tool which may help and reinforce the understanding of the involved physical phenomena is developed. It may also offer a support for results analysis and solve inverse problem (determination of the corresponding elastic modulus C^*_{ij}).

2 HYDROTHERMAL AGEING - DRYING MONITORING OF COMPOSITE MATERIALS USING ULTRASONIC GUIDED WAVES

The sensitivity of ultrasonic guided waves to various levels of moisture in a carbon-epoxy plate has been investigated during a PhD performed in collaboration with the Laboratoire de Mécanique Physique (Bordeaux 1 University). The results presented in this paper have been obtained for a laminate composite plate made of material used on rocket motor case (2D woven, carbon fibres and epoxy matrix plies). The plate thickness is (5.3 ± 0.3) mm and its density is (1.5±0.1). First of all, the viscoelasticity moduli $C_{ij}= C'_{ij}+i\ C''_{ij}$ of the material are measured using a classical immersion ultrasonic technique [3]. Then the composite plate undergoes cycles of hydrothermal ageing and drying. It is placed during four months in a steam oven at 65°C and with 70% of moisture until it reaches a state close to saturation. This is controlled by following changes in the plate weight, which tends to a plateau limit when saturation is reached. Then a drying process is applied. The composite plate is placed in an oven at 65°C during two months, after which its weight gets back to its initial value. For various steps of these cycles, both changes in weight and ultrasonic data are measured. Low-order A0, S0, A1, S1 guided modes are generated and detected using air-coupled transducers and signal processing allows both real and imaginary parts of the wave-numbers to be measured. Several measurement campaigns are performed in order to evaluate the reproducibility of the results.

The experimental campaigns are carried out by using the guided waves generation/detection set-up presented in Figure 1. Two air-coupled capacitive transducers [4] are placed on the same side of the tested sample to allow single-sided access and contact-less NDT.

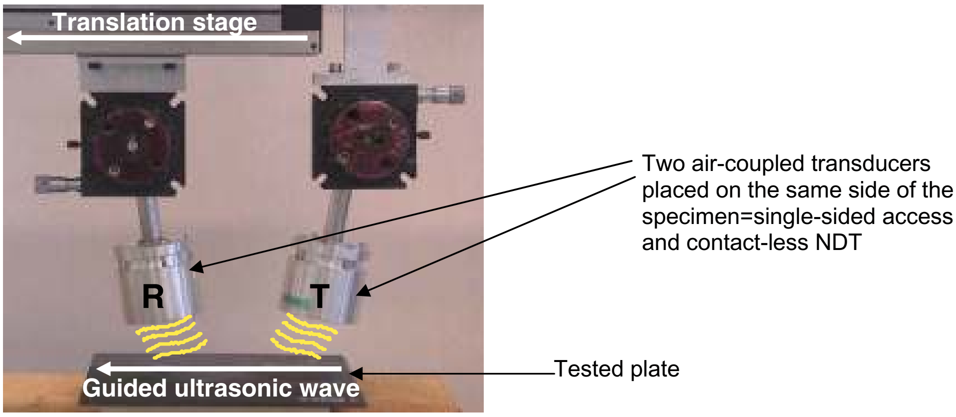


Figure 1: Single-sided, contact-less ultrasonic experimental set-up.

The real parts of the wave-numbers (k’) of all the generated modes are shown to be not sensitive to the moisture level of the material (Figure 2, left). However the imaginary part of the wave-number (k’’), i.e. the attenuation, of the A0 mode is very sensitive to the moisture content as shown on Figure 2 (right).

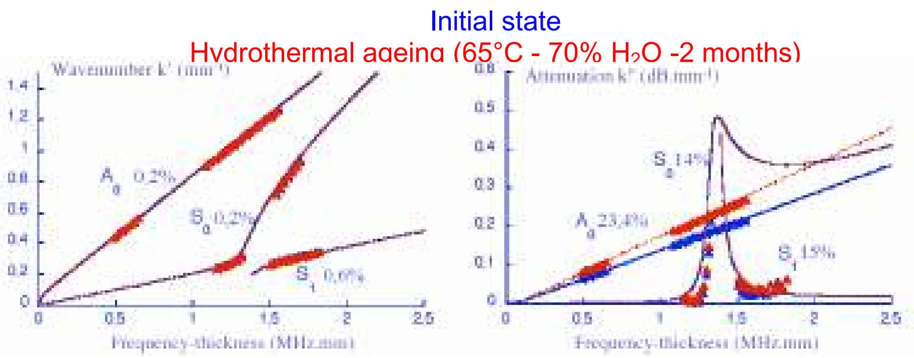


Figure 2: Measurements (triangles) and numerical predictions (lines) before (blue) and after (red) hydrothermal ageing; (on the left) real (k’) and (on the right) imaginary parts (k’’) of wave-numbers.

The same sensitivity is demonstrated for the drying process (Figure 3).

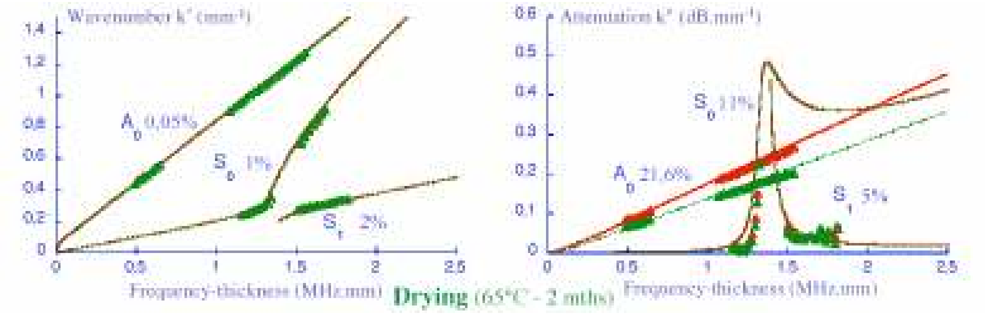


Figure 3: Measurements (triangles) and numerical predictions (lines) before (red) and after (green) drying; (on the left) real (k') and (on the right) imaginary parts (k'') of wave-numbers.

The relative changes in A0 mode attenuation $\left(\frac{\Delta k''}{k''}\right)$ during ageing-drying processes follow very well those of the plate weight (Figure 4). This parameter that is directly linked to the imaginary part of the Coulomb modulus in the plane of propagation (C''66) seems thus a good indicator of the moisture content in this composite material.

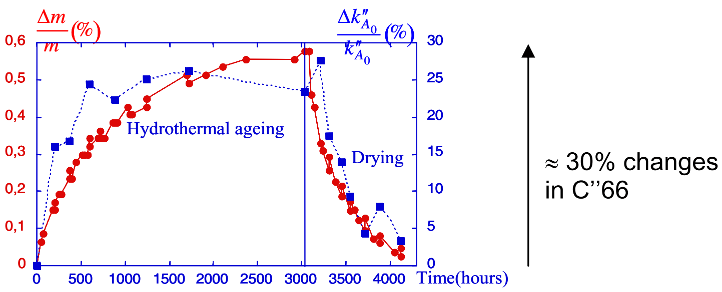


Figure 4: Correlation between relative change in weight and relative change in A0 mode attenuation $\left(\frac{\Delta k''}{k''}\right)$.

3 MICROCRACKING MONITORING OF COMPOSITE MATERIALS USING ULTRASONIC GUIDED WAVES

The second part of the research works aimed to investigate the sensitivity of ultrasonic guided waves to micro-cracks (different microcracking rates) induced by low temperature exposure of composite materials.
Eight composite plates theoretically leading to increasing microcracking rates have been manufactured with M55J/M18 material:
-Plate I: $[0/+45/90/-45]_{6S}$ (x3),
-Plate II: $[0_2/+45_2/90_2/-45_2]_{3S}$ (x3),
-Plate III: $[0_3/+45_3/90_3/-45_3]_{2S}$ (x2),
the 45° plies preventing the initiation of delamination.

The mechanical characteristics of each composite plate have been measured with Lamb waves identification process at the initial state E1. Then several thermal cycling were performed on these samples: -50°C (E2), -100°C (E3), -150°C (E4) and liquid nitrogen at -196°C (E5, E6, E7). After each exposure, guided waves measurements were performed on the plates. In parallel, microscopic examination was performed on samples extracted from the plates to observe the micro-cracks appearing and increasing.

The Figure 5 illustrates the sensitivity of the tested guided waves (real part of the wave-number k') to microcracking appearing (confirmed by micrographic observation). The results obtained for the imaginary part of the complex wave-number k'' do not highlight any consistent evolution with the micro-cracking. The effect of lay-up sequence on the microcracks density has been emphasized by Lamb waves measurements and microscopic observations (Figure 5). Moreover, this sensitivity has been correlated to helium leakage measurements performed on each sample at the E7 state (Figure 6). Lastly, a good reproducibility of the results have been obtained and confirmed that the A0 mode is a good indicator of composite materials micro-cracking.

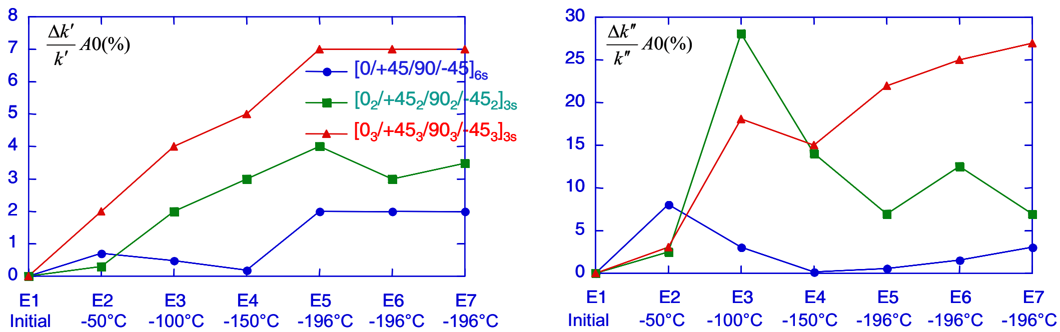


Figure 5: Sensitivity of the A0 wave-number (real part k') to microcracking in carbon epoxy plates (left) and evolution of the imaginary parts of wave-numbers (k'') (right)

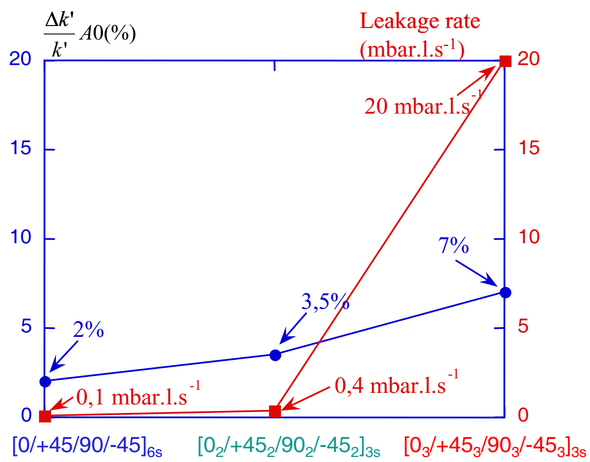


Figure 6: Correlation between the A0 wave-number (real part k') and the leakage rates measured on the three plates having different stacking sequences.

4 MONITORING OF ADHESIVE JOINTS USING ULTRASONIC GUIDED WAVES

There is currently a growing use of bonding in aerospace and other industries because this kind of joint allows lighter structures and more uniform stress distribution compared to bolting, riveting and spot welding. Due to manufacturing conditions or degradations during service of the adhesive joint, several problems may occur (localized problems such as delamination, cracks, cohesive and adhesive problems such as ageing or pollution) and deteriorate the adhesive joint performances. Thus non destructive methods able to assess and control the structural adhesive joint integrity during manufacturing, and throughout the service life of the products (health monitoring) are continuously investigated. In this frame, an increasing attention is given to ultrasonic methods [5] that may provide a great deal of information on the adhesive-bonded joint. Conventional ultrasonic methods may detect gross flaw such as void and delamination. But the adhesive problems are more difficult to detect with classical technique, for instance in case of adhesive disbond in which the adherends remain in intimate contact ("kissing bond"). Ultrasonic guided waves are very attractive method because their physical nature is different from the bulk waves used for classical techniques and they provide a fundamentally different approach (propagation down the plate instead of through the plate). Thanks to their stress distribution inside the plate thickness, they are sensitive to the mechanical properties of the adhesive (cohesive properties) and to the boundary conditions between the adhesive and the substrates (adhesive properties)

A relation between mechanical performance and ultrasonic guided waves response has been demonstrated at ASTRIUM-ST for specific cases of adhesive joint (test samples with polluted interfaces). On the basis of these first experimental results, ASTRIUM-ST has focused his approach towards a fundamental study based on the sensitivity demonstration of ultrasonic guided waves to adhesive bonding quality on academic materials (different interface conditions (surface roughness, pollution, compressive loading…) and different cohesive properties of the glue (stiffness, polymerisation degree...)). Experimental works have been conducted on academic materials (elastomer, aluminium) with simple bonding geometries in order to demonstrate and reproduce the sensitivity results. In parallel to these experimental investigations, a modelling tool which may help and reinforce the understanding of the involved physical phenomena has been developed.

Preliminary works conducted in collaboration with the Laboratoire de Mécanique Physique (BORDEAUX 1 University) have been performed on the bonding configuration shown on Figure 7 to investigate elementary cases of interfaces and coupling conditions. The ultrasonic guided waves are generated in the aluminium plate, propagate through the joint and are collected after the joint for post-processing.

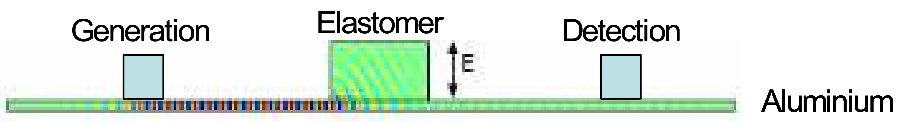
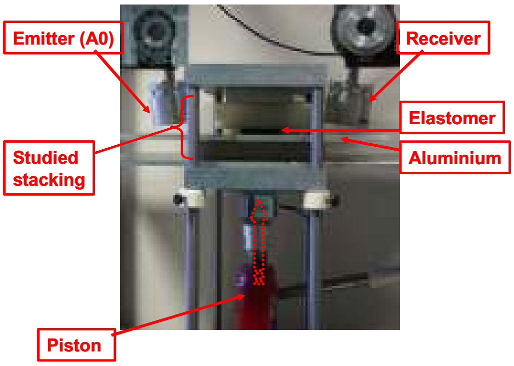


Figure 7: Studied configuration.

Several kinds of surface conditions have been tested: rough and smooth surfaces of elastomer. The sensitivity of A0 and S0 modes to the coupling between elastomer and aluminium created by a pressure force applied on the stacking (without glue in a first stage) has been demonstrated (Figure 8).



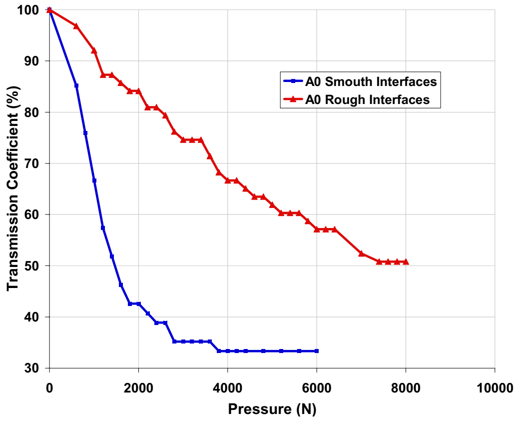


Figure 8: Experimental set-up used to apply a controlled pressure on the elastomer/aluminium stacking (left) and evolution of the A0 transmission coefficient with the pressure applied on the elastomer-aluminium stacking (right).

Moreover the sensitivity of the A0 and S0 modes to adhesively bonded interfaces (glue AF3109) in opposition to compressed interfaces has been demonstrated experimentally using an elastomer with rough surfaces (Table 1).

Rough surfaces	**Transmission coefficient A0 mode (%)**	**Transmission coefficient S0 mode (%)**
Compressed (no adhesive bond)	51%	66%
Adhesive bond (not compressed)	33%	83%
Adhesive bond and compressed	33%	75%

Table 1: Measurements of the transmission coefficients through compressed and adhesive bonded rough interfaces.

In addition, some experimental tests have been performed on the same stacking (elastomer/aluminium) introducing a slow reticulating glue (Loctite 9461 A&B) between the two layers (assessment of the influence of the cohesive properties of the glue). For this configuration, the A0 mode has demonstrated a significant sensitivity to the properties (modulus) of the glue evolving with time (Figure 9) whereas the S0 mode transmission does not change with the reticulation of the glue. The final value reached by the A0 mode transmission is similar to the one obtained for the AF3109 glue (~35%).

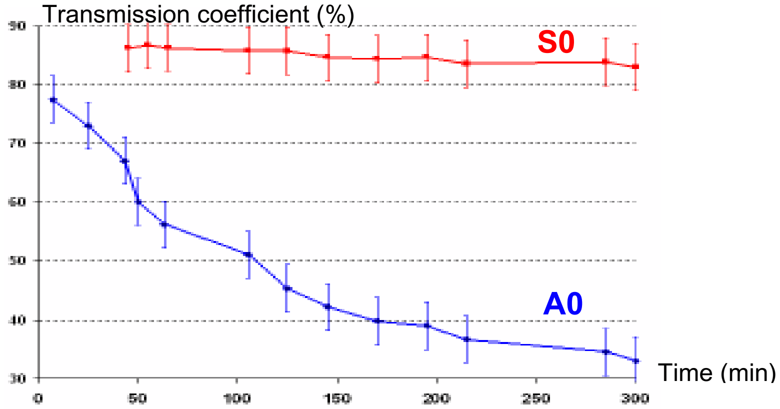


Figure 9: Evolution of A0 and S0 transmission coefficient with the reticulation time.

In parallel to these experimental investigations, a modelling tool (finite element approach) is being developed [6]. The “Glue layer model” and the “Springs model” (Table 2) simulating the mechanical characteristics of bonding have been implemented on the FE modelling tool allowing to simulate the ultrasonic wave propagation.

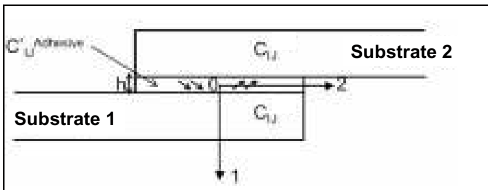
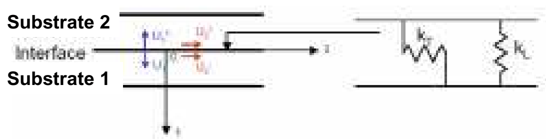
	
Continuity of stress and displacements at interface, adhesive layer characterized by its viscoelastic coefficients, thickness and density	Adhesive layer reduced to an interface characterized by K_L and K_T (normal and tangential stiffnesses)

Table 2: Glue layer model (left) and Springs model (right).

The glue layer model was confronted to experimental measurements performed on an adhesive lap joint shown between two aluminium plates (configuration shown on Figure 10). The viscoelasticity moduli C_{11} and C_{66} of the adhesive material have been measured using an immersion ultrasonic technique. A first comparison has been made between FE model and experimental measurements on samples manufactured with AF3109 glue.

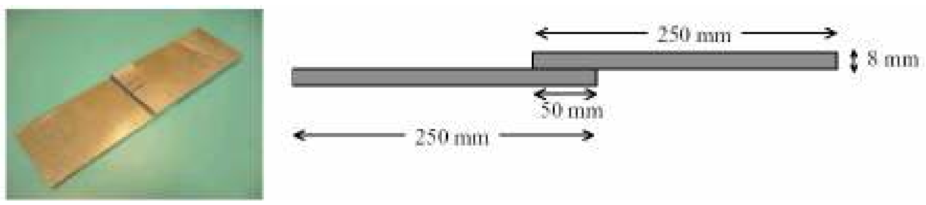


Figure 10: Geometry of adhesive lap joints studied.

A good correlation between modelling and measurements was obtained for the glue layer model (see Table 3).

	FE model	**Experiment**
Reflection coefficient	0.19	0.15
Transmission coefficient	0.81	0.80

Table 3: Comparison between FE model results and experimental measurements of reflection and transmission coefficients.

5 CONCLUSIONS

The non-destructive method using ultrasonic guided waves is very promising as regard to the first results obtained for moisture content and microcracking detection in composite material. The results dealing with assessment of adhesive bonding strength are also encouraging but a great deal of work is required in order to demonstrate the correlation between ultrasonic parameters and bonding strength obtained by mechanical destructive tests.

In parallel to experimental investigations, a modelling tool taking into account the ultrasonic wave propagation and the mechanical characteristics of the materials is absolutely required in order not only to provide a guide for the choice of experimental conditions and reinforce the understanding of the involved physical phenomena but also to offer a support for results analysis (inverse problem).

A great deal of work is also necessary to transpose this method to industrial applications and develop reliable systems for continuous autonomous self monitoring of composite characteristics and adhesive bonding performances.

6 REFERENCES

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